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MEMORANDUM**

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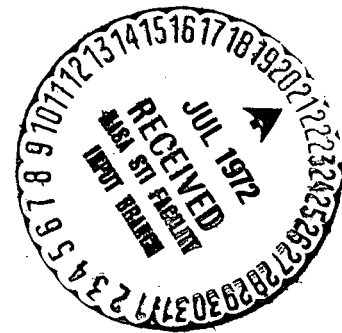
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**TRANSONIC TRANSPORT STUDY – ECONOMICS**

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## SUMMARY

An economic analysis was performed to evaluate the impact of advanced materials, increased aerodynamic and structural efficiencies, and cruise speed on advanced transport aircraft designed for cruise Mach numbers of .90, .98, and 1.15.

A detailed weight statement was generated by an aircraft synthesis computer program called TRANSYN-TST; these weights were used to estimate the cost to develop and manufacture a fleet of aircraft of each configuration. The direct and indirect operating costs were estimated for each aircraft, and an average return on investment was calculated for various operating conditions.

There was very little difference between the operating economics of the aircraft designed for Mach numbers .90 and .98. The Mach number 1.15 aircraft was economically marginal in comparison but showed significant improvements with the application of carbon/epoxy structural material. However, the Mach .90 and Mach .98 aircraft are the most economically attractive vehicles in the study.

## INTRODUCTION

The economic performance of an aircraft is a prime factor in the decision of any commercial operator to invest in new equipment. Improvements in speed, comfort, or convenience are strong selling features, but sales will not occur unless the aircraft can also be shown to yield an attractive return on investment. Technology advances usually provide an increase in productivity and/or a decrease in the operating cost of the aircraft.

These improvements are not obtained without cost, however, and it must be determined if the improvements are sufficient to offset the required investment.

An economic analysis of advanced transport aircraft was performed by the Advanced Concepts and Missions Division as part of a study of the application of technology advances to commercial aircraft. The objective of this study was an evaluation of the economic performance of long-range transports utilizing the increased aerodynamic efficiency possible with supercritical wings and area-ruled bodies and the increased structural efficiency possible with composite materials. Aircraft designed for cruise Mach numbers ranging from .90 to 1.15 were investigated to assess the economic impact of increased cruise speed.

This report presents the results of the economic analysis and briefly describes the methods used. An overall summary of the complete study and its conclusions is given in reference 1. More detailed evaluations of the aerodynamics and structures and the propulsion system are given in references 2 and 3, respectively.

#### METHOD OF ANALYSIS

The analyses of the performance and economics of the aircraft were performed with the aid of an extensive array of computer programs developed by the Advanced Concepts and Missions Division. A vehicle synthesis program called TRANSYN-TST was used with a parameter optimizer program, AESOP, (reference 4) as the basic working tool for calculating the aircraft characteristics. The program computes the aerodynamic and propulsive performance of the aircraft and performs a structural analysis and a weight and size estimation. Vehicle weight, thrust, and fuel requirements are determined

as a function of the payload and range specified. These results are transferred to the economic programs where the aircraft acquisition costs and operating economics are computed.

A total of six aircraft were investigated; table 1 compares their characteristics. The study vehicles are designated as a conventional transport (CVT), with a cruise Mach number of .90; an advanced technology transport (ATT), with a cruise Mach number of .98; and a transonic transport (TST), with a cruise Mach number of 1.15. Each vehicle was investigated as an all-aluminum configuration and as a configuration with all-carbon/epoxy (C/E) fuselage and wings. All six of the configurations used a supercritical wing and high bypass ratio turbofan engines, and all had a 2700 n. mi. range carrying 200 passengers. The Mach .98 vehicle (ATT) and the Mach 1.15 vehicle (TST) had area-ruled fuselages.

Figure 1 illustrates the flow of information in the analysis of the aircraft economics. The output of the vehicle synthesis program, such as component weights, engine thrust, and other physical characteristics, constitutes the input to the acquisition cost program which estimates the development and production costs of the aircraft. The output of this program is the unit acquisition cost of the aircraft and engines, and this in turn is input to the economic program which estimates operating costs and ROI.

### Aircraft Price

The unit acquisition cost of the aircraft is determined by amortizing the estimated research, development, test, and evaluation (RDT&E) costs over the total projected sales, and adding this to the average manufacturing cost estimated for the vehicle. Both RDT&E and manufacturing costs are

estimated using cost estimating relationships developed from historical aircraft cost data. Table 2 summarizes the cost elements comprising the RDT&E and production phases. Regression techniques were used to develop cost estimating relationships based on physical characteristics such as the aircraft weight and speed, component weights, engine thrust, etc. The effects of learning, aircraft production rate, profit, and other factors are included in the estimation of production costs.

The formulas used to calculate the costs are based on data from aluminum aircraft and use weight as the primary estimating parameter. In order to account for the weight differences and design variations between aircraft constructed of carbon/epoxy and those constructed of aluminum, complexity factors were applied to the basic cost estimating equations.

The results of the synthesis program output indicate that the weight ratio between an aircraft constructed of C/E and an equal size aircraft constructed of aluminum is 0.66. That is, the C/E aircraft weighs about 34% less than the aluminum aircraft. It is assumed that the time to design the same size piece would be the same for both materials. This combination yields an engineering complexity factor of 1.5 for carbon/epoxy construction versus aluminum construction on a per-pound basis.

The method used to derive the manufacturing complexity factor is illustrated in table 3. For 250 units the average labor requirement is three hours per pound with conventional aluminum construction. The labor requirement for C/E was assumed to be 80% greater than for aluminum, so an average of 5.4 man-hours are needed for one pound of manufactured C/E. At a labor rate of \$15 per hour the resultant labor cost is \$45 per pound for aluminum and \$81 per pound for C/E. The material cost must be added to this.

Carbon/epoxy material consists of approximately 50% carbon filaments with an estimated cost of \$20.00 per pound in 1985 and 50% epoxy at an estimated cost of \$17.50 per pound. Based on these figures, one pound of raw C/E material would cost \$18.75 in 1985. The corresponding cost of aluminum raw material averages about \$2 per pound. However, in order to yield one manufactured pound of aluminum, approximately three pounds of raw material are required because of wastage in the manufacturing process (machining losses, rejected parts, etc.). Since C/E material is laid into molds, a smaller wastage factor--30%--was assumed. Hence, the material cost used in estimating the cost of the final manufactured product was \$6 per pound for aluminum and \$25 per pound for C/E.

For 250 units, the average total manufacturing costs per pound of aluminum and C/E structure, including both labor and material, are \$51 and \$106, respectively. Using aluminum costs for the nominal reference value, the resulting manufacturing complexity factors are 1.0 for aluminum and 2.0 for C/E.

Table 4 tabulates the final values of the complexity factors used for the study vehicles. The manufacturing complexity factors used for the aluminum wing and fuselage are greater than 1.0 because all aircraft use the supercritical wing and all except the CVT use area-ruled fuselages. It is expected that these new design features would entail an additional manufacturing complexity relative to conventional aluminum structure. The C/E vehicles use the 2.0 manufacturing complexity factor derived in table 3.

The engineering complexity for the aluminum ATT and TST, again because of the complex wing and fuselage shapes, is assumed to be greater than the factor for the conventional aircraft in aluminum; in this case, a value of 1.2 is used to reflect the complexity. For C/E aircraft, an engineering complexity factor of 1.5, as derived above, is used.

Tooling costs will also be different for carbon/epoxy structures than those for aluminum due to the differences in fabrication procedure. Unfortunately, actual tooling data is very limited, because carbon/epoxy structural components built to date have been fabricated under carefully controlled conditions rather than in a normal production environment. In this study a nominal complexity factor of 1.0 was used for all C/E aircraft. Because of the lower structural weight of the C/E aircraft, total tooling cost is lower.

### Operating Cost

Operating costs are divided into direct and indirect operating costs; the elements which comprise each of the two categories are listed in table 5. The 1967 Air Transport Association (ATA) equations (ref. 5) were used to compute direct operating costs (DOC) and the 1970 Civil Aeronautics Board (CAB) methods (ref. 6) were used for the indirect operating costs (IOC). Since the costs for the study are presented in 1970 dollars, correction factors were applied to the equations where there was a need to account for inflation. For example, maintenance labor rates were increased from \$4/hr to \$5/hr, and flight and cabin crew rates were increased to reflect 1970 wage scales.

Following is a list of assumptions used in the cost analysis:

- (1) 1970 Dollars;
- (2) 9 hr/day Utilization;
- (3) 0.0164 \$/lb Fuel Cost;
- (4) 50% Load Factor;
- (5) 250 Aircraft Fleet; and
- (6) 12 Year Depreciation Period.

These assumptions reflect current airline experience in load factors, fuel cost, utilization, and depreciation period. Since all vehicles were assumed to have the same utilization (9 hrs/day), the faster vehicles show a greater productivity.

### Return On Investment

While operating cost per seat-mile is an important indicator of the efficiency of an aircraft, the projected return on investment (ROI) is the measure of economic productivity used to justify investment in new equipment. In this context, ROI measures the ability of the aircraft to return to the investor the value of the investment, plus a profit, over a designated life span. The ROI will frequently, but not always, be greatest for the vehicle which has the lowest seat-mile operating cost.

Return on investment may be defined in many ways. However, since ROI is most useful in a relative sense, the method chosen is usually less important than is the consistency with which it is applied. For this study the ratio of annual cash flow generated by the aircraft to the initial investment was used.

The annual cash flow is the sum of the net profit and depreciation. It is computed as the after-tax difference of annual revenue and operating costs, where operating costs are defined to exclude depreciation. Taxes are computed at the standard rate of 48% of net profits. The annual revenue is estimated by multiplying the number of seat-miles flown per year times an average revenue yield. The average seat-mile revenue was estimated by correlating current airline fares with distance traveled, assuming 20% first class and 80% coach class seating. A 10% fare dilution was assumed to account for the effect of family plans, excursion rates, and other special promotional fares.

The investment is the initial value of the aircraft plus spares. The spares ratio assumed is 10% of the airframe price plus 40% of the total cost of engines, in keeping with ATA recommendations. It should be noted that the new wide-body jets are frequently operated with a somewhat lower inventory of spare engines--about 25%. Although the use of 25% engine spares would increase the indicated ROI slightly, the effect on the comparison of the different aircraft within the study would be negligible.

## RESULTS

### Comparison with Existing Aircraft

In order to validate the TRANSYN-TST computer program, the technical characteristics, performance, and operating economics of the 707-120B and the 747B were synthesized. The results of the economic analysis of these two aircraft will be briefly described.

Unit selling prices, based on a fleet of 250 aircraft and fully amortized RDT&E costs, of \$9.0 million and \$22.4 million were computed by TRANSYN-TST for the 707-120B and 747B, respectively. The actual selling price of these aircraft in 1970 dollars would be about \$8 million to \$9 million for the 707-120B and \$23 million to \$24 million for the 747B. These estimates are based on the data of figure 2, which shows the average selling prices of commercial aircraft as a function of empty weight.

While the computed values of unit price are considered good for both the 707-120B and 747B, it is much more difficult to validate the estimation of operating costs. Both DOC and IOC vary widely with range, load factor, utilization, and other operating conditions, and also from operator to operator. Further, while DOC data is available by aircraft type, the very

nature of indirect operating costs restricts the manner in which they are collected and reported. Total indirect costs for all flight operations are reported annually by each airline; these costs are allocated by functional category (e.g., cabin crew, food, baggage handling, etc.) rather than by aircraft type or distance traveled. Accordingly, the IOC for a specific aircraft type must be estimated based on average costs per passenger mile.

Figure 3 compares the estimated values of DOC and IOC to the currently reported values for the 747B. The DOC computed for the conditions shown agrees very well with the 1.08 cents/seat-mile average DOC actually achieved by the 747 in 1970. The computed IOC is somewhat lower than the value estimated for actual operation, 0.80 cents/seat-mile. Note that 1970 was the first year of 747 operation, however, and the IOC should decline with increased operating experience.

#### Economics of Advanced Transport Aircraft

Baseline Comparison.- The synthesis program was employed to estimate the economics of the advanced transport aircraft analyzed in this study; the results are shown in figure 4. In this figure, the price, operating costs, and return on investment are compared for all six study vehicles. Each of the aircraft were optimized as explained in reference 1. Examining the aluminum aircraft first, the CVT has the lowest average unit price, only slightly more expensive than the present generation of stretched jet aircraft. The ATT unit price is slightly higher, primarily because it is a heavier airplane with a larger structural weight fraction (due to the area-ruled body and higher wing sweep) and larger engines, but its DOC is only .02 cents/seat-mile higher than the CVT.

It is important to recognize that the only components of DOC which are affected by airplane price are depreciation, insurance, and maintenance

materials. Since these total about 50% of the DOC, the net effect of a 10% increase in airplane price is only about a 5% increase in direct operating costs, or a 2 1/2 to 3% increase in the total operating cost. The effect on ROI is more significant, since ROI is inversely proportional to price (because of the effect on investment). Thus, the ATT has a slightly lower ROI despite its higher productivity relative to the CVT.

The aluminum Mach 1.15 vehicle (TST) is not attractive economically. It is a much larger and heavier aircraft, due to higher aerodynamic drag and higher structural weight fraction. The gross weight and empty weight are both more than twice that of the ATT aircraft designed for the same range and payload. As a result, the unit price is about 60% more than that of the ATT, the DOC is about 50% greater, and the ROI is about 40% lower than those of the ATT or CVT.

When carbon/epoxy material is used, the economics show some variations. The ATT now has a slightly higher ROI than the CVT and is slightly higher than the aluminum CVT. The net effect of C/E is that the operating economics of both the ATT and CVT are modestly improved. The unit price of both aircraft is increased slightly despite the reduced size and weight resulting from the greater structural efficiency of carbon/epoxy. The effect of composites is greatest for the Mach 1.15 airplane; the large reduction in size and weight results in reductions in unit price and operating cost of about 20% and increases the ROI by 40%. However, the aircraft still is not economically competitive with the subsonic vehicles.

Complexity Factor Investigation.- There is, of course, considerable uncertainty in estimating the cost of designing and fabricating aircraft out of carbon/epoxy. Therefore, the effect of more optimistic complexity

factor assumptions was investigated. The engineering and tooling complexity factors for a C/E vehicle were set equal to those of an aluminum vehicle. That is, the design and tooling costs per pound for C/E structure were assumed to equal those for aluminum; since the C/E airplanes are lighter weight for the same mission, a reduction in both engineering and tooling costs for the same size piece of structure results. For manufacturing complexity, aluminum and carbon/epoxy were assumed to require equal labor hours per pound (3 hrs/lb), while the material costs were left unchanged. The new manufacturing complexity factor for C/E is 1.4 as opposed to 2.0 for the baseline comparison.

Figure 5 illustrates the economics of the C/E and aluminum vehicles with the new complexity factor assumptions. The prices for C/E aircraft are now lower than aluminum aircraft for all three study vehicles, as are the operating costs. As before, the carbon/epoxy ATT is the vehicle with the highest ROI of all the configurations studied. Also, the improvement in the TST yields a more favorable economic outlook for this aircraft.

Effect of Raw Material Costs.- A raw material cost of \$20/lb for carbon filaments was used throughout the analysis. This is the projected price for the mid-1980's. In order to assess the effect of changes in raw material cost on ROI, costs for the carbon filaments were varied while the price of epoxy was held constant at \$17.50/lb. Figure 6 shows the results of this sensitivity analysis with the complexity factors from the baseline comparison being used. The asterisk (\*) marks the ROI for the reference aluminum vehicles. Note that there is only a slight advantage gained by use of composites on the two subsonic aircraft (CVT and ATT) even with very low carbon filament prices. This is because the higher labor costs

of designing and manufacturing out of C/E are retained in this analysis. However, the TST has sufficient structural efficiency gains with carbon/epoxy that its ROI is better than the aluminum TST even for very high carbon filament prices.

Effect of Fare and Load Factor.- Two other study variables which are of interest are the fare and load factor assumptions. The fare level assumed was the current domestic fare (first class and coach) for the nominal flight distance of the study. A fare dilution of 10% was applied to account for the effects of family plans, excursion rates, and other special promotional fares. All vehicles were studied at a nominal 50% load factor in both first class and coach sections. It might be argued, however, that the reduced trip time for the faster cruising ATT or TST would attract passengers from the conventional transports on competitive routes. Thus a higher load factor and/or a small fare surcharge might be possible with the faster aircraft. The ATT and TST were compared with the CVT to determine what load factor, or fares would be necessary for the aircraft to yield an ROI equal to that of the aluminum CVT with current domestic fares and a 50% load factor. Figure 7 is a plot of the load factor/fare surcharge combination for the aluminum ATT and the aluminum and C/E TST's which result in a value of ROI equal to that of the aluminum CVT. The ATT and CVT are nearly equal; the aluminum TST would require a 76% load factor at the same fare or a 45% fare surcharge at the same load factor (or some intermediate combination) to yield the same ROI as the aluminum CVT.

The comparison of the carbon/epoxy TST aircraft and the aluminum CVT shows that the TST performance is greatly improved, but it is debatable whether or not the reduction in trip time (one hour coast-to-coast) would

increase the load factor to 60% or support a fare surcharge of 25% to make the airplane attractive economically.

### CONCLUSIONS

The results of this study indicate that there is very little difference between the operating economics of the Mach .90 CVT and the Mach .98 ATT advanced transport configurations. The use of carbon/epoxy structural material offers little advantage for either aircraft if the baseline material complexity factors used in this study are valid. If design and fabrication experience with composite materials reduces the future value of these complexity factors, however, a Mach .98 carbon/epoxy aircraft will look increasingly attractive economically.

The aluminum Mach 1.15 TST is economically unattractive due to its large size and weight and the resulting high operating cost. Because the aluminum TST performance is so marginal, the increased structural efficiency resulting from the application of carbon/epoxy to the TST yields significant improvements in terms of reduced size, lower price and operating cost, and a higher return on investment. For the configurations of this study, however, these gains do not change the conclusion that the Mach .90 and Mach .98 vehicles are more economically attractive.

#### REFERENCES

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2. Ardema, Mark D. and Williams, Louis J.: "Transonic Transport Study - Structures and Aerodynamics," NASA TM X-62,157, May 1972.
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4. Hague, D. S. and Glatt, C. R.: "A Guide to the Automated Engineering and Scientific Optimization Program--AESOP," NASA CR-73201, June 1968; and "An Introduction to Multivariable Search Techniques for Parameter Optimization (and Program AESOP)," NASA CR-73200, April 1968.
5. Air Transport Association: "Standard Method of Estimating Comparative Direct Operating Costs of Turbine Powered Transport Airplanes," December 1967.
6. Civil Aeronautics Board: "Costing Methodology, Domestic Fare Structure," Docket 21866-7, Exhibit No. BC-3999, Version 6, August 1970.

	DESIGN MACH NUMBER	GROSS TAKEOFF WEIGHT, WGTO	WING SWEEP, $\Delta$ , deg	ASPECT RATIO, $\bar{A}$	WING LOADING, W/S	SUPER- CRITICAL WING	AREA RULED BODY
CVT	AL	214,500	35	6.8	123	YES	NO
	C/E	182,500	35	9.1	113	YES	NO
ATT	AL	232,500	41	8.1	123	YES	YES
	C/E	189,000	41	12.4	106	YES	YES
TST	AL	504,000	50	6.4	127	YES	YES
	C/E	323,000	50	9.8	100	YES	YES

TABLE 1.- STUDY AIRCRAFT CHARACTERISTICS

RDT AND E  
AIRFRAME DESIGN  
PROPULSION DEVELOPMENT  
TOOLING  
FLIGHT TEST VEHICLES  
FLIGHT TEST OPERATIONS  
  
PRODUCTION  
OPERATIONAL VEHICLES  
SPARES AND GSE  
PRODUCT SUPPORT  
TRAINING

TABLE 2.- ACQUISITION COST ELEMENTS

	ALUMINUM	CARBON/EPOXY
• LABOR		
hr /lb	3.0	5.4
\$/lb		
(@ \$15 /hr )	45	81
• MATERIAL		
FILAMENT \$/lb	—	20
EPOXY \$/lb	—	17.50
COMPOSITE \$/lb	—	18.75
ALUMINUM (\$/lb)	2	
BUY/FLY RATIO	3	1.3
TOTAL \$/lb	6	25
• MANUFACTURING COST (\$/lb)	51	106
• MANUFACTURING COMPLEXITY		
FACTOR	1.0	2.0

TABLE 3.- MANUFACTURING COMPLEXITY FACTOR ESTIMATION

## MANUFACTURING

### ALUMINUM

#### WING

1.10

#### FUSELAGE

1.25 (1.0 IF  $M < 0.92$ )

#### CARBON / EPOXY

2.00

### ENGINEERING

#### ALUMINUM

1.20 (1.0 IF  $M < 0.92$ )

#### CARBON / EPOXY

1.50

### TOOLING

#### ALUMINUM

1.00

#### CARBON / EPOXY

1.00

TABLE 4.- COMPLEXITY FACTORS

DIRECT OPERATING COST

FLIGHT CREW

FUEL AND OIL

INSURANCE

MAINTENANCE— FLIGHT EQUIPMENT

DEPRECIATION— FLIGHT EQUIPMENT

INDIRECT OPERATING COST

MAINTENANCE — GROUND EQUIPMENT

DEPRECIATION — GROUND EQUIPMENT

PASSENGER SERVICES

AIRCRAFT AND TRAFFIC SERVICING

GENERAL AND ADMINISTRATIVE

TABLE 5.— OPERATING COST ELEMENTS

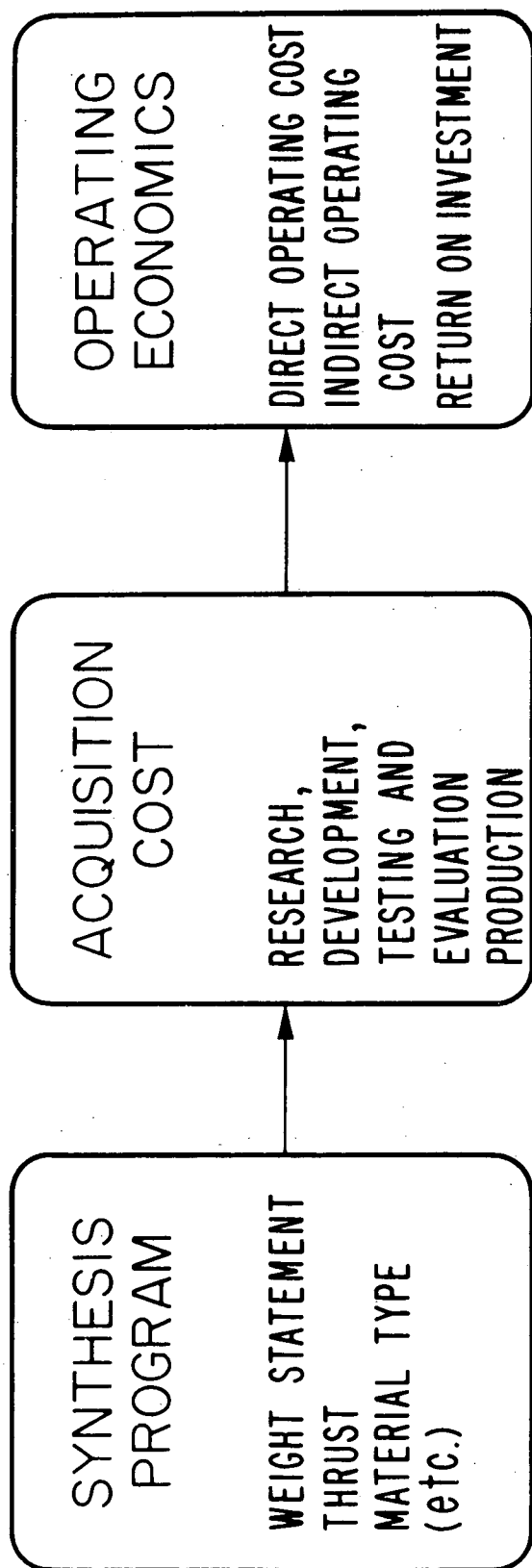


FIGURE 1.- ECONOMIC ANALYSIS

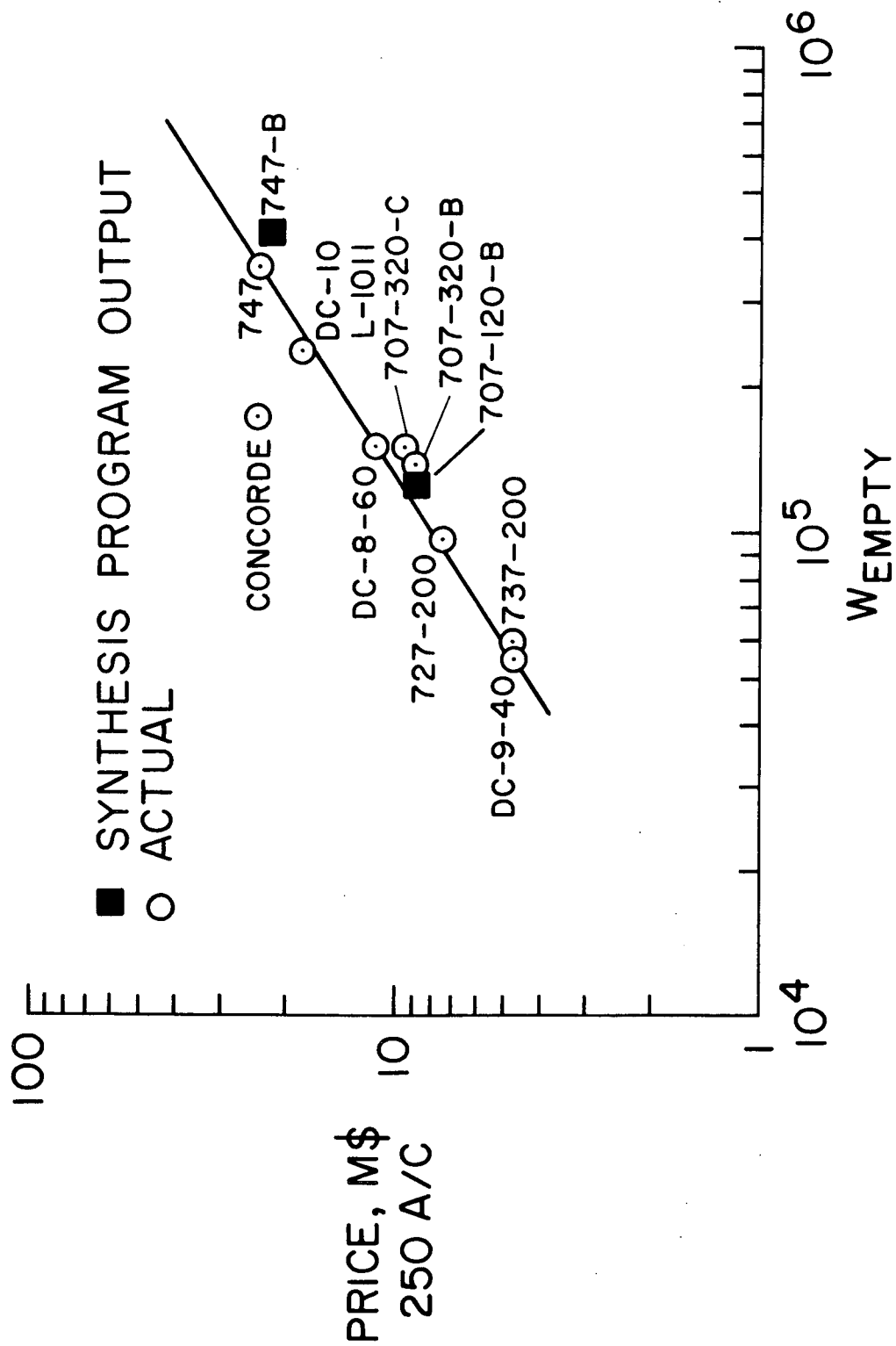


FIGURE 2.- PRICES OF AIRCRAFT IN CURRENT PRODUCTION

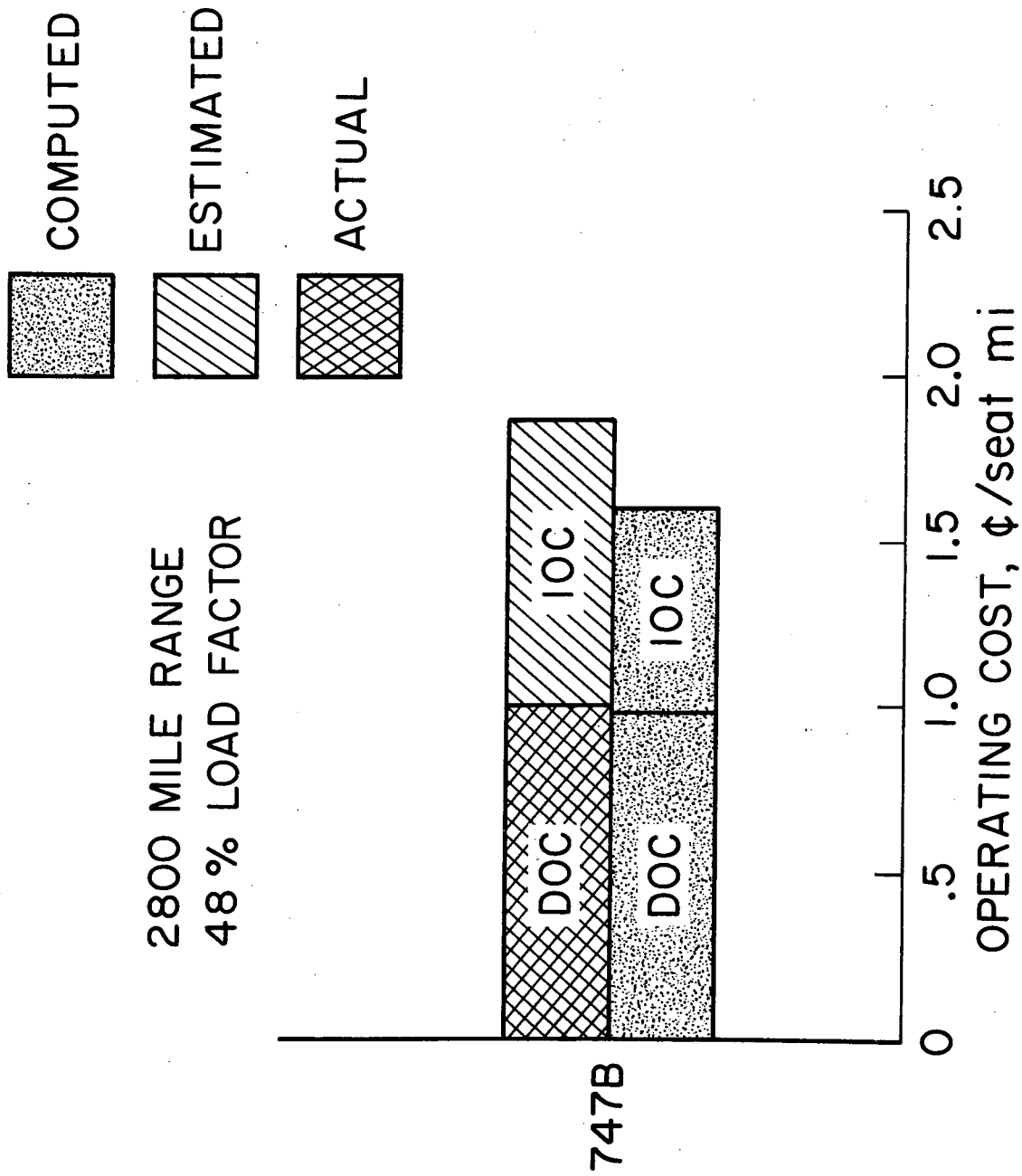


FIGURE 3.- OPERATING COST COMPARISON - 747B

# OPTIMUM CONFIGURATIONS

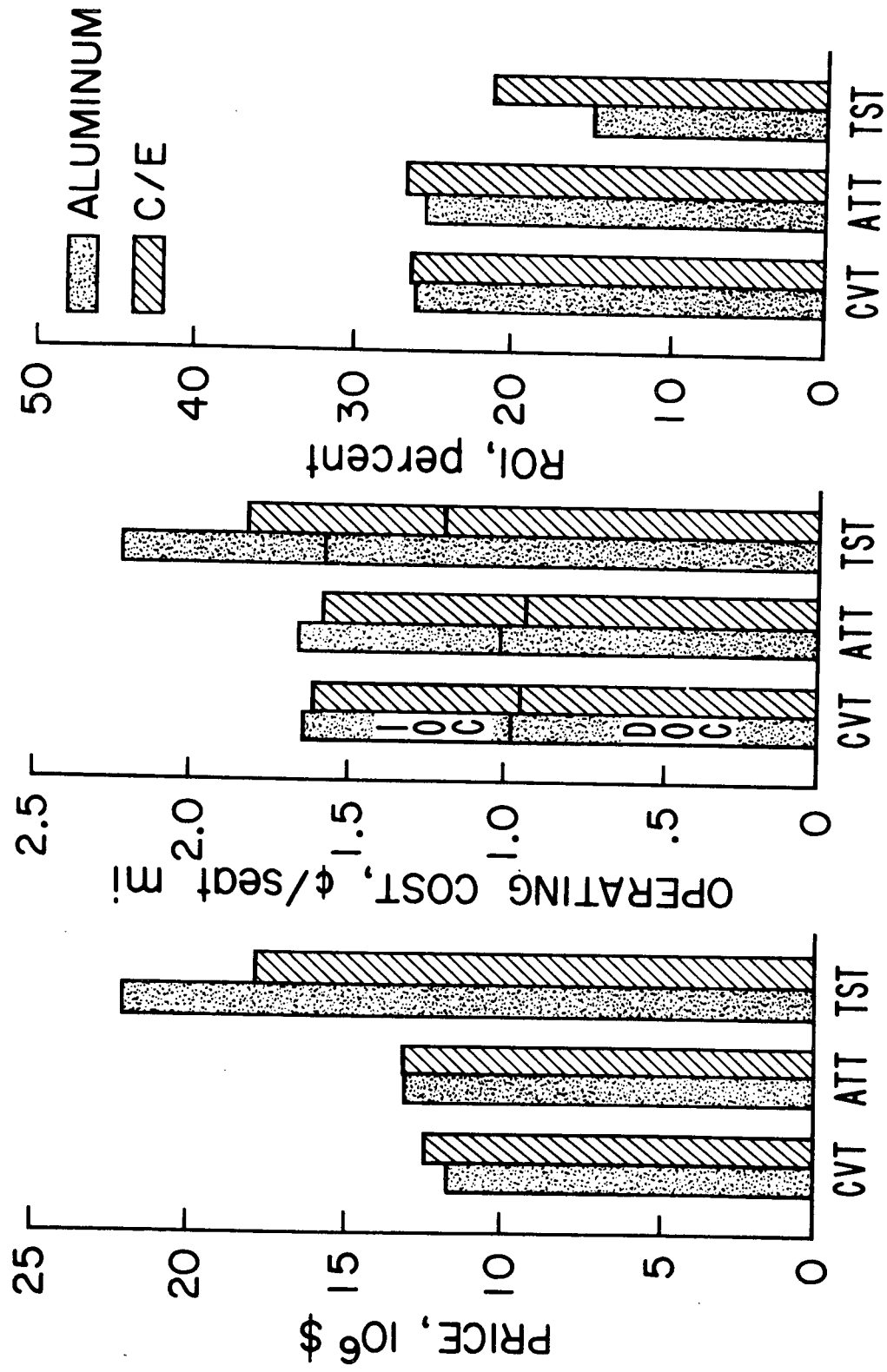


FIGURE 4.- AIRCRAFT ECONOMIC COMPARISON

# OPTIMUM CONFIGURATIONS

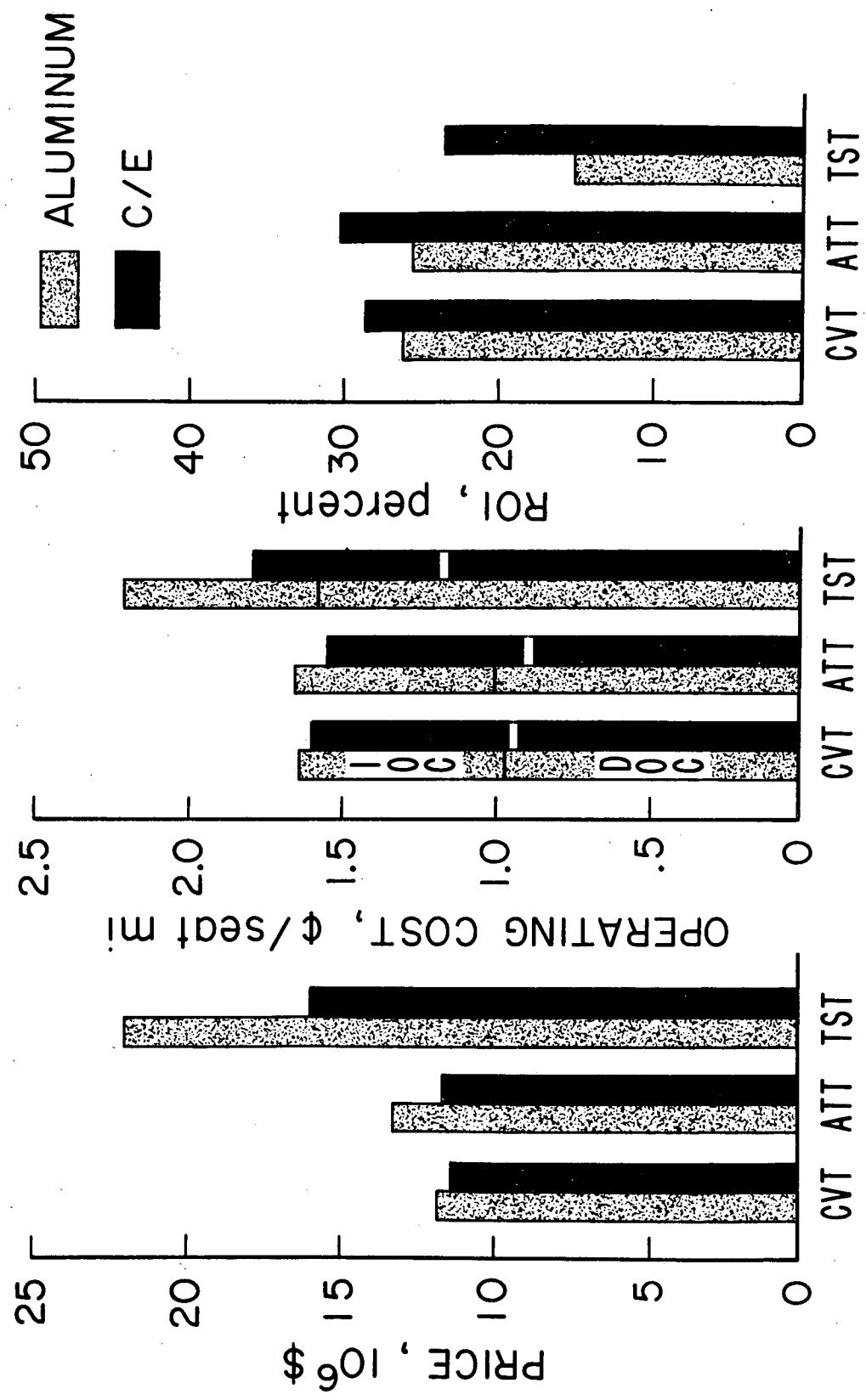


FIGURE 5.- AIRCRAFT ECONOMIC COMPARISON - OPTIMISTIC COMPLEXITY FACTORS

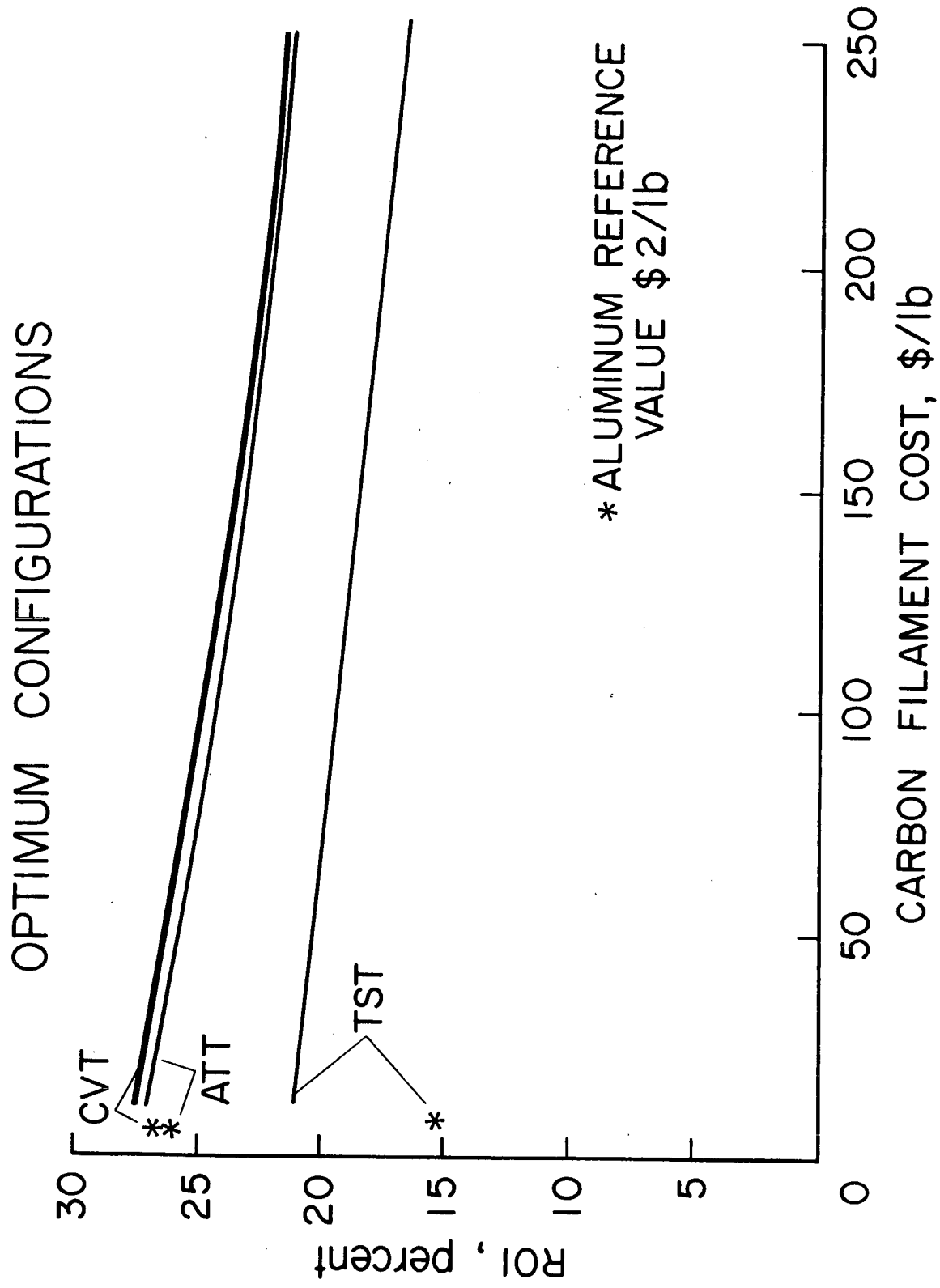


FIGURE 6.- EFFECT OF MATERIAL COST ON RETURN ON INVESTMENT

# OPTIMUM CONFIGURATIONS

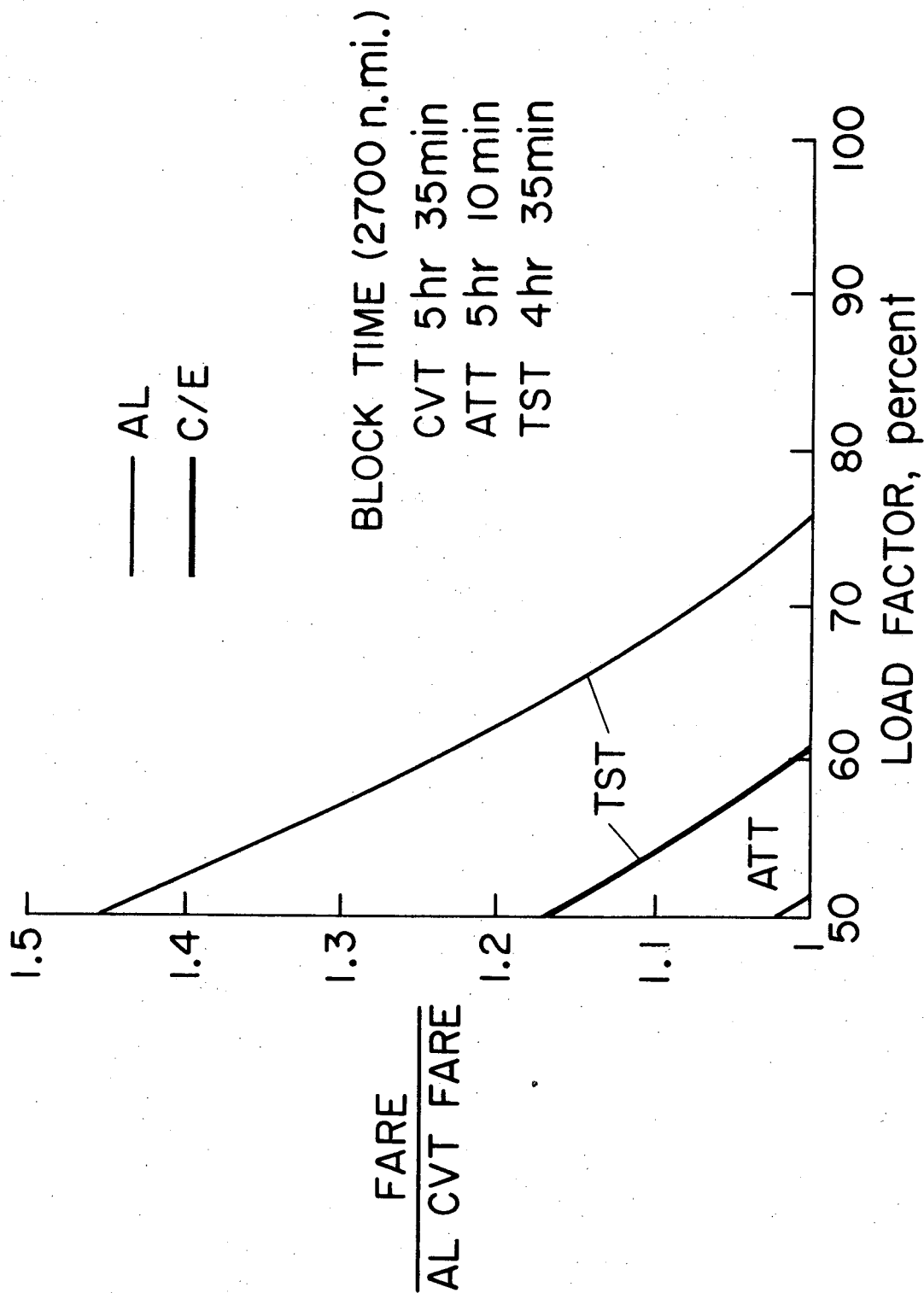


FIGURE 7.- FARE REQUIRED FOR EQUAL RETURN ON INVESTMENT